FINAL REPORT

AN EXPERIMENTAL PROGRAM TO DETERMINE THE SENSITIVITY OF EXPLOSIVE MATERIALS TO IMPACT BY REGULAR FRAGMENTS

Contract No. DA-19-020-ORD-5617
PA Control No. PA-AG-62-1

prepared for

COMMANDING OFFICER
PICATINNY ARSENAL
DOVER, NEW JERSEY

by

D. G. McLEAN AND D. S. ALLAN
ARTHUR D. LITTLE, INC.
CAMBRIDGE, MASSACHUSETTS

DECEMBER 29, 1965

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FOREWORD

This work was administered under the direction of the Process Engineering Laboratory of the Ammunition Engineering Directorate at Picatinny Arsenal, Dover, New Jersey. Mr. R. Rindner was Project Engineer for the Laboratory. Technical contributions were also made by Messrs. L. Saffian and S. Wachtell.

ABSTRACT

An experimental program was conducted to establish the sensitivity of explosives to the impact of regular steel fragments. Non-spinning rectangular fragments of 0.2 to 3.0 ounces were projected by explosive means at velocities both above and below that required for detonation. Velocities were measured by screens and by high speed photography.

All data were obtained using either Pentolite or Cyclotol explosives. The results of the tests were compared with a relationship between fragment mass and boundary velocity (below which detonation will not occur) established by Picatinny Arsenal and based on data from small fragment tests. The tests with uncased charges tended to confirm the predicted relationship for all fragment weights fired at Pentolite and for the small and intermediate fragments fired at Cyclotol. A modification in the predicted mass velocity relationship may be required to more accurately define the boundary velocity for heavy fragments (3.0 oz) impacting in Cyclotol.

These tests demonstrated that with uncased charges the Picatinny Arsenal relationship will tend to be conservative when used to predict boundary velocities for safety purposes.

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I. INTRODUCTION

This program is concerned with the experimental determination of the sensitivity of explosives and propellants to impact by high velocity particles. It is the purpose of the project to establish the relationship between limiting fragment mass and impact velocity required for the detonation of specific explosives and/or propellants. The resulting data are for the use of Picatinny Arsenal in studies relating to the safe design of explosive facilities.

In this program it is required that non-spinning rectangular steel fragments of 0.2 to 3.0 ounces be impacted into explosives at velocities that are both above and below that necessary for detonation to occur. The fragments are to have a length to width ratio not to exceed 2.5. The velocity of the fragments is to be measured by timing screens and/or high speed cameras and the occurrence of detonation is to be determined by the condition of a one-inch thick mild steel witness plate placed to the rear of the receiver charge. An hypothesis as to the relationship between fragment mass, velocity, and receiver charge casing thickness to cause detonation of specific explosives has been formulated by Picatinny Arsenal* and was used as a guide in the experiments.

*Rindner, R.M., "Establishment of Safety Design Criteria for Use in Engineering of Explosive Facilities and Operations," Report Number 2, Detonation by Fragment Impact, May 1959, Picatinny Arsenal Report DB-TR: 6-59.

II. SUMMARY

In this program all testing utilized an explosive technique for projecting the rectangular steel fragments. This involved the application of methods devised in previous work but required considerable effort early in the program to meet specific test conditions (see Appendix A). Verification of fragment velocities was achieved by photographing the fragments with high speed cameras. The integrity of the fragments was established in numerous firings where the fragment was recovered and examined. Recorded velocities were estimated to be accurate to within two percent.

All of the tests were conducted at the New Hampshire test facility of Arthur D. Little, Inc. All receiver charges and some donor charges (for propelling the fragments) were furnished by Picatinny Arsenal. A total of some 37 valid tests were made with explosive charges protected by different thicknesses of steel plates (cased explosives) and some 55 tests with bare (or uncased) charges. The explosives used for the sensitivity tests were Pentolite and Cyclotol.

There was an insufficient number of tests for the establishment of the fragment (boundary) velocities required for the detonation of the cased charges. However, the data did indicate that the boundary velocities were, in general, consistent with the results of tests with uncased charges. The experimentally determined boundary velocity values for uncased charges tended to confirm the Picatinny Arsenal relationship for all fragment weights fired at Pentolite and for the small and intermediate weight fragments fired at Cyclotol. A modification in the mass-velocity relationship may be required for predicting the sensitivity of Cyclotol to the impact of heavy fragments.

The results of this work suggest that additional tests be made to insure that these trends are statistically valid.

III. EXPERIMENTAL PROGRAM

A. The Establishment of Boundary Velocities

The purpose of the experimental program is to obtain data which can be used to establish the boundary velocity as a function of fragment weight and casing thickness for different explosives. The boundary velocity for a specific fragment weight and type of explosive covered with a given casing thickness is defined as that velocity below which no high order detonation would occur. A relationship between fragment weight (m, oz), the boundary velocity (V_s, ft/sec) and casing thickness (t, in) has been established by Picatinny Arsenal and was used as a guide in conducting the experiments. This relationship, or model, is as follows:

$$V_s^2 = \frac{Ke^{(5.37\ t/m^{1/3})}}{m^{2/3}\ (1 + 3.3\ t/m^{1/3})}$$

where K is a constant that depends upon the sensitivity of the specific explosive being investigated. The values of K were derived from a large number of experiments conducted by different agencies in the past. It is our understanding, however, that both the constant and the relationship itself is, primarily, based on experiments with relatively light fragments.

The expression derived by Picatinny Arsenal has been plotted in Figures 1 and 2 showing the boundary velocities for Pentolite and Cyclotol for the range of fragment weights, velocities, and casing thicknesses of interest.

In this program boundary velocities were determined by conducting a number of tests with a given fragment weight, explosive and casing thickness.

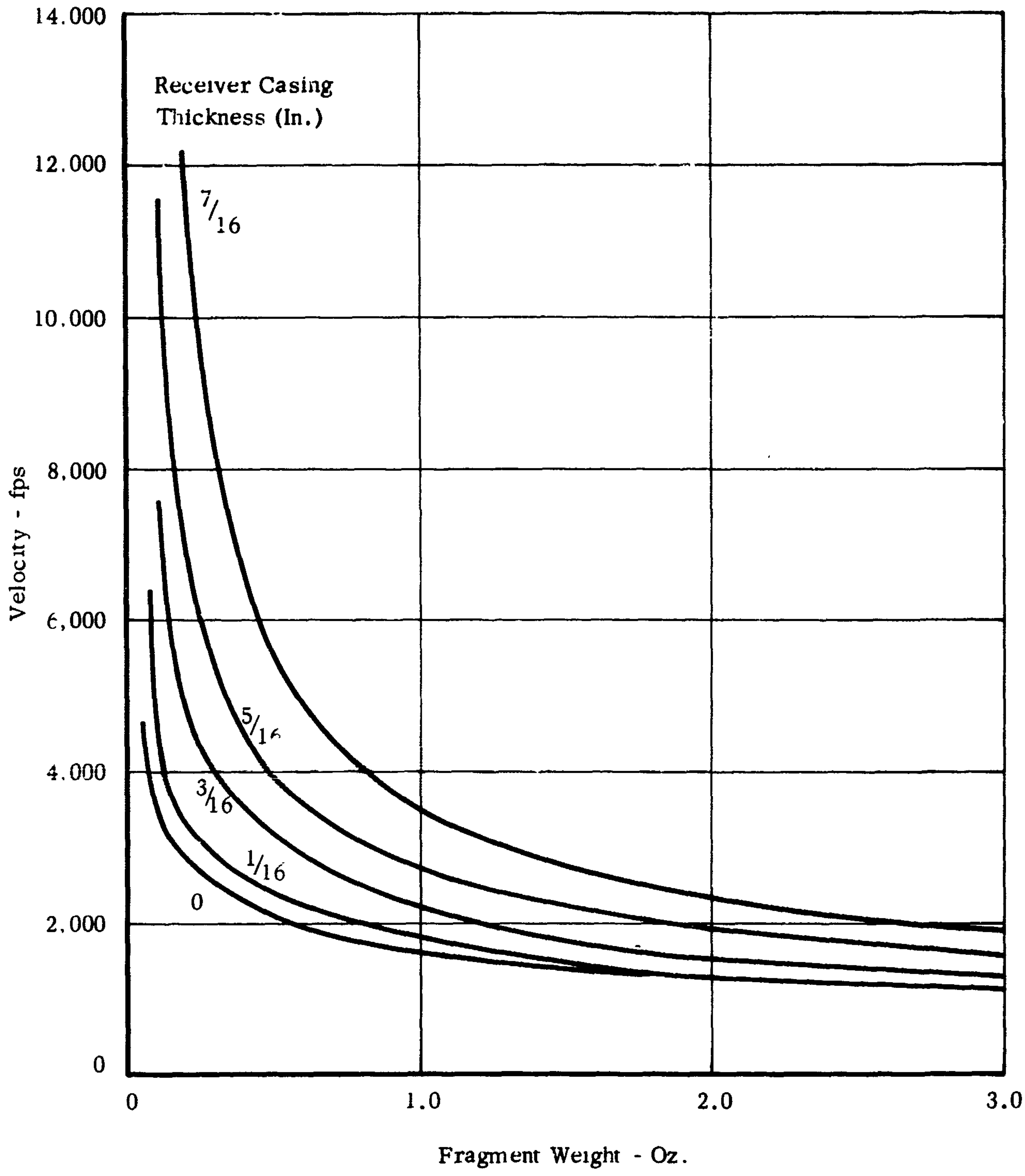


FIGURE 1 BOUNDARY VELOCITY AS A FUNCTION OF FRAGMENT WEIGHT - PENTOLITE (Ref. 1)

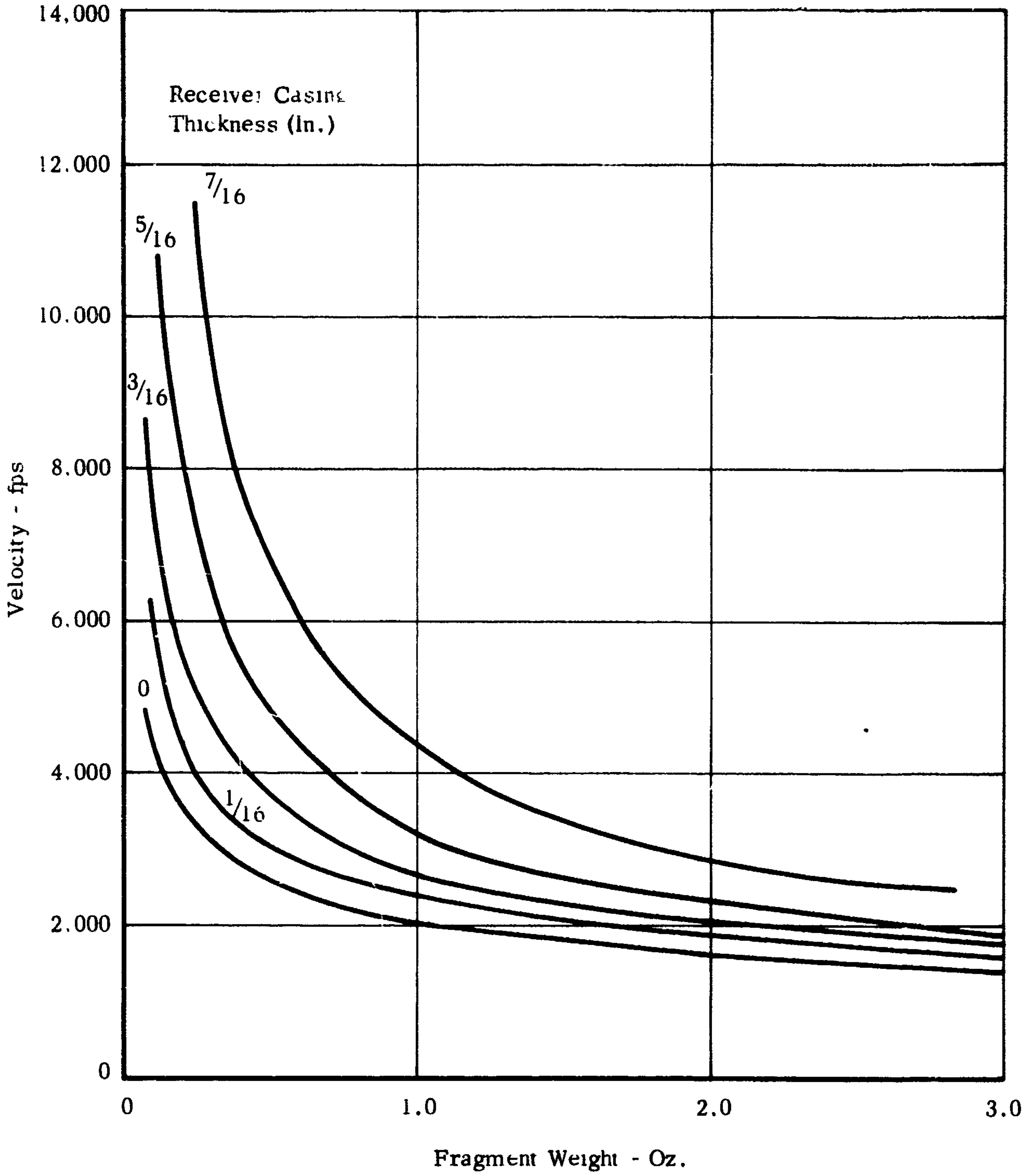


FIGURE 2 BOUNDARY VELOCITY AS A FUNCTION OF FRAGMENT WEIGHT - CYCLOTOL (Ref. 1)

The velocity was varied in each test so that a relatively small velocity interval could be established below which no detonations occurred and above which detonations occurred in every test.

B. General Test Procedure

The explosive launching technique used in this program consists of the placement of the fragment, its surround, and an attenuating sheet of lucite on the forward face of the cylindrical explosive donor. The lucite spacer (buffer plate) reduces the impulse imparted to the fragment and provides a means of altering the launch velocity. The fragment is surrounded by four pieces of equal thickness of steel which prevent deformation at the edges of the fragment during the early stages of launch (Figure 3).

The cylindrical charge is initiated by means of a detonating cap and a 25 gram Tetryl booster placed on the rear face of the explosive. Upon detonation the fragment is propelled, undamaged, along a predictable path and, in these experiments, impacted the target (reciever charge) at a distance of approximately six feet. The surround material also travels a predictable path which radiates outward from the axis of flight of the primary fragment at greater than a 13^{o} angle and hence does not impact with the receiver charge. The velocity of the impacting primary fragment is measured by accurately positioned timing sensors and in most cases confirmed by high speed photographs of its flight. Fragment velocity, over rather wide limits, is controlled by the size and composition of the donor charge and the buffer plate thickness. The maximum velocities attained in these tests without fragment damage were 5200, 3500, and 2700 feet per second for 0.2, 0.9 and 2.85 ounce fragments respectively.

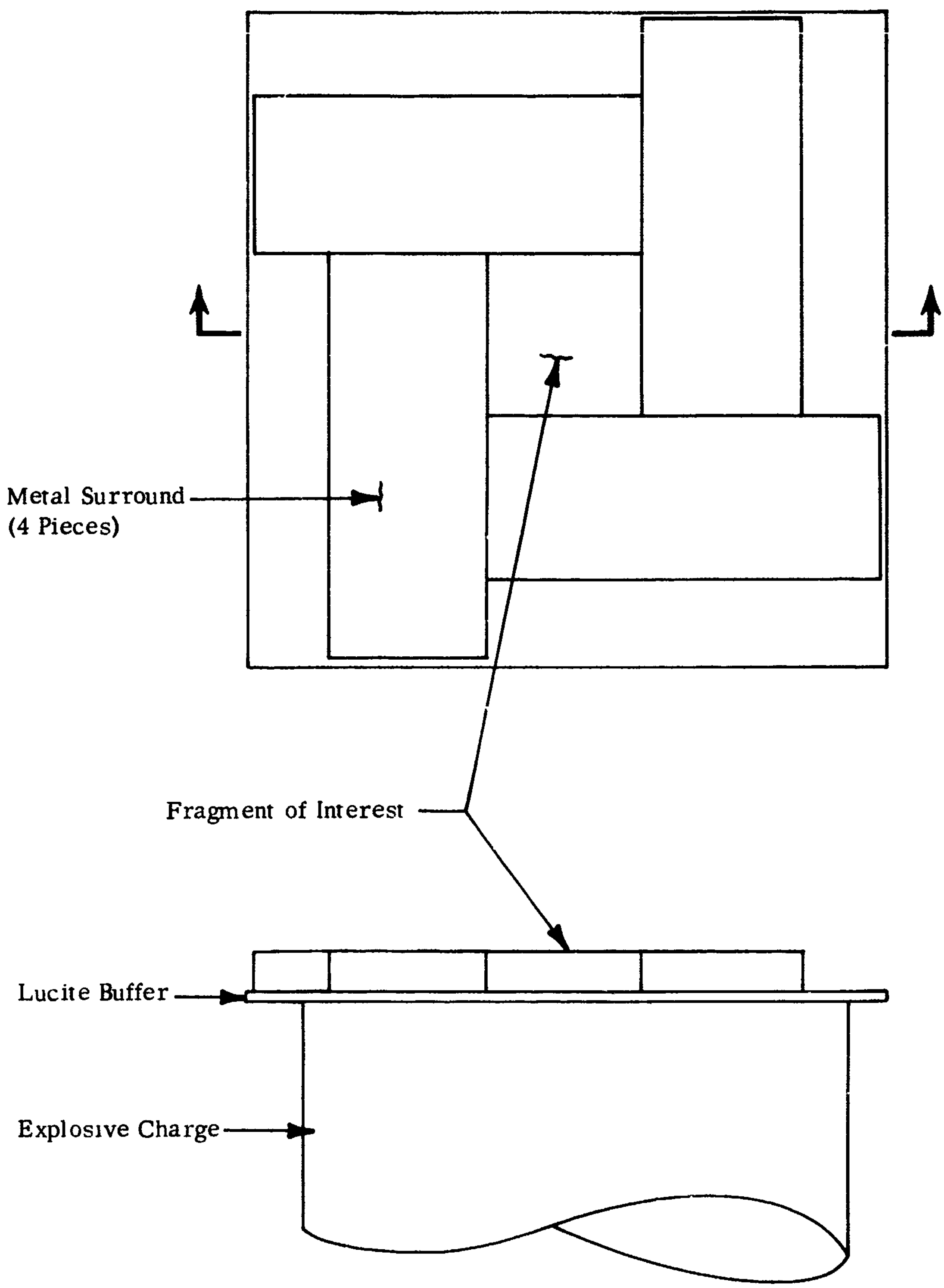


FIGURE 3 FRAGMENT ARRANGEMENT WITH METAL SURROUND

The fragment accelerating (donor) charges used in various phases of this program ranged in size from 2 to 8 inches in diameter and from 2 to 8 inches in length. The receiver charges consisted of a steel cylinder, 6 inches in diameter and length filled with the cased explosive. The casing (or cover plate) was placed over one end of the cylinder and a flat mild steel (6 x 6 x 1 inch) witness plate at the other end. The cover and witness plates were tied together with long bolts external to the receiving charge.

The witness plate was used to determine whether a high order detonation occurred as a result of fragment impact. It was agreed that if reaction of the explosive caused a fracture or deformation of the surface of the plate of greater than 1/8 inch in depth than it would be assumed that a high order detonation took place. In all the tests in this program the explosive reaction was either high order with severe damage to the witness plate or burning and no deformation of the plate. The experimental arrangement used in this program is shown in Figure 4.

C. Fragment Aiming Procedure

Figure 5 depicts the technique used to insure that the fragment would impact the center of the receiver charge. The donor charge assembly is placed at the top of the seven foot high stand and the receiver charge is centered vertically below it. The telescope and 45° angle mirror assembly is then located with the mirror over the desired impact point and the brass plate perpendicular to the axis of the receiver charge. While sighting through the scope, the donor charge assembly is positioned so that the fragment can be clearly seen. Another mirror is then placed

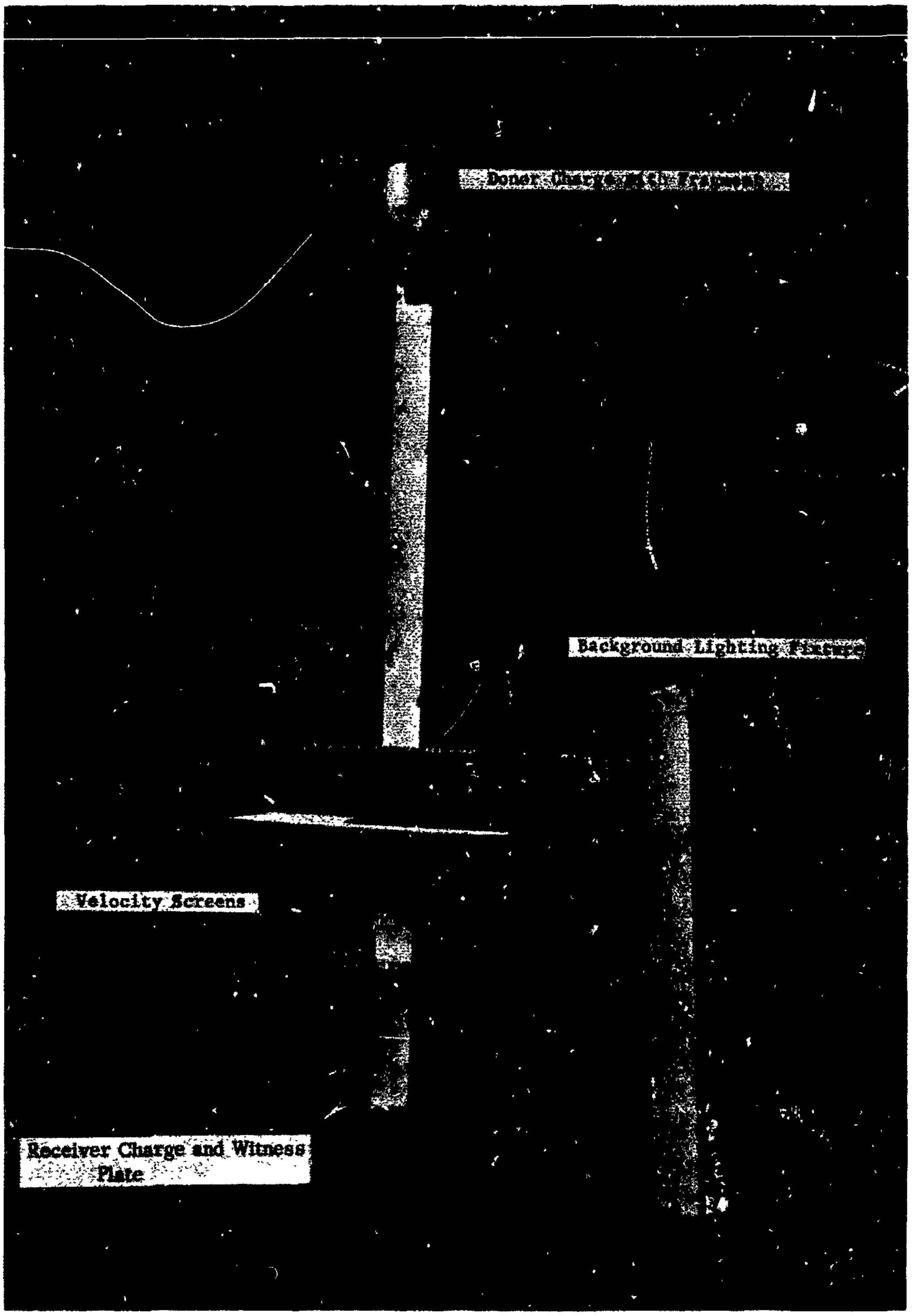


FIGURE 4 TEST SETUP

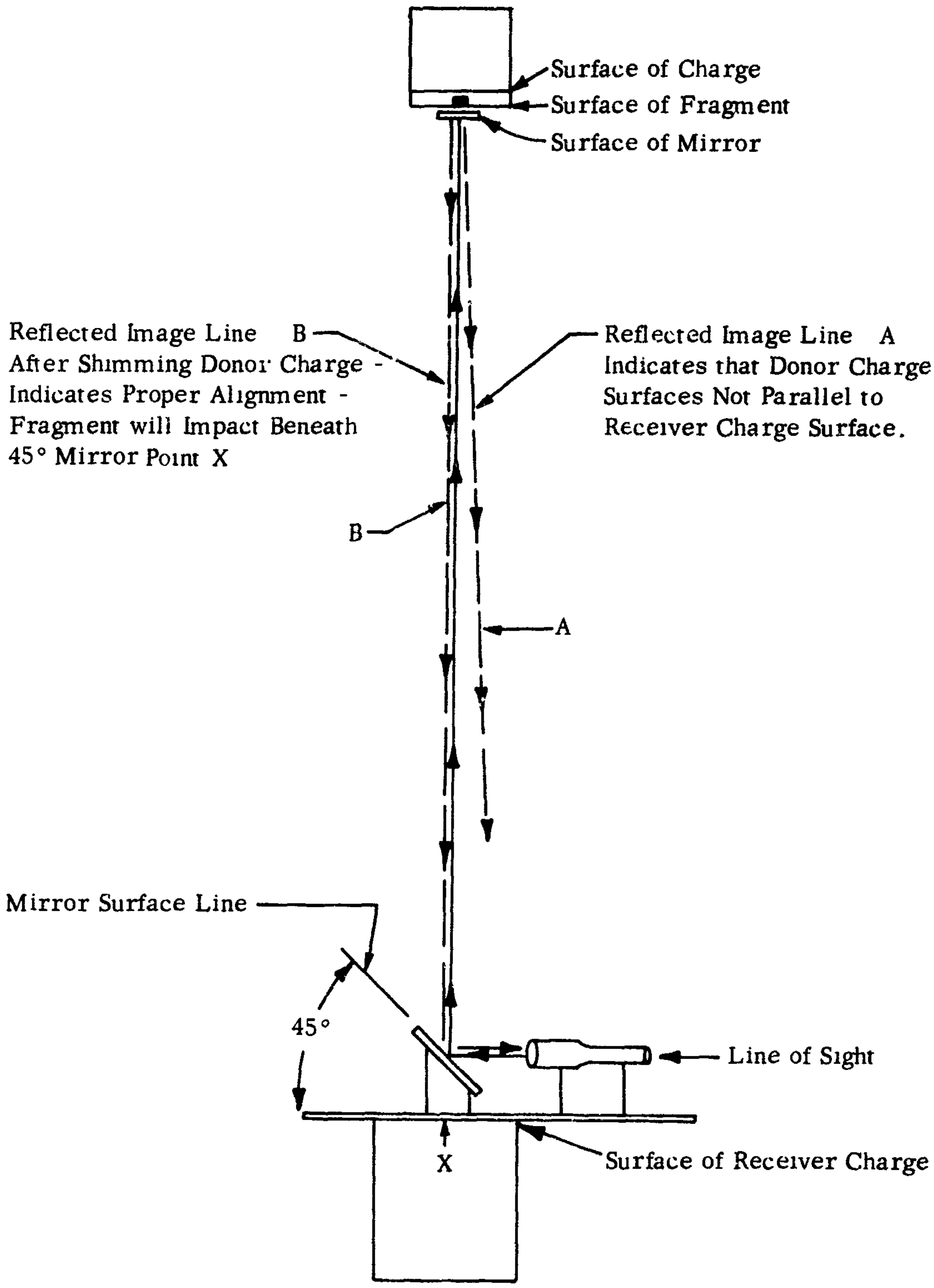


FIGURE 5 SCHEMATIC: FRAGMENT AIMING TECHNIQUE

on the fragment (held by a magnet) parallel to the surface of the fragment. While sighting through the scope, the donor charge is shimmed, until the reflected image of the telescope end is centered in the eyepiece.

It was demonstrated that this aiming procedure is reliable and can be carried out in a relatively short period of time.

Once the aiming has been completed, the mirror and scope assembly are removed, velocity screens located, and all final electrical connections made. The test set up is then ready to fire.

D. Instrumentation

The principle instrumentation consisted of time measuring devices positioned so that the time for fragment travel between two accurately measured points could be recorded on Model 7260 Bechman Time Interval Meters. A Dynafax drum camera, having a framing rate up to 25,000 frames/second, photographed the fragment in flight.

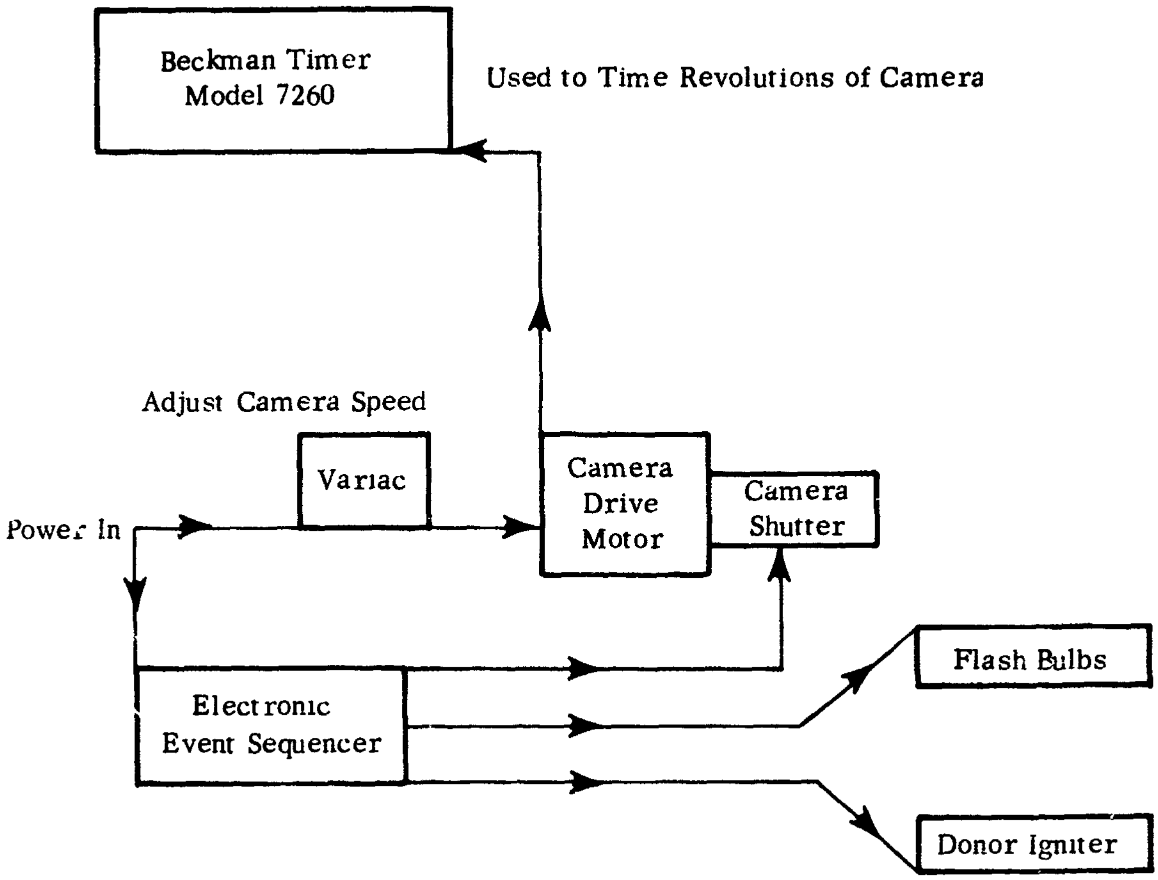
The timing devices consisted of an ionization probe and a pair of screens made from sheets of aluminum foil separated by a thin piece of polyethylene film. The ionization gage was taped to the donor charge and the screens were located on the forward face of the receiver charge and at a specified distance above the receiver charge. Velocities were computed from the measured fragment travel time and the known distance between the sensors. The Dynafax camera was located in a bunker approximately 20 feet from the flight path and viewed approximately the last four feet of travel, including target impact. Back lighting was provided by 12 PF#22 flash bulbs wired in parallel and timed to coincide with the fragment flight and camera shutter

opening. (Figures 6 and 7 diagram schematically the instrumentation). The film strip was developed and in most cases analyzed within 30 minutes after each firing.

E. Calibration Firings

A series of experiments were made to assess fragment damage and to establish the fragment velocity versus bufferplate thickness. These firings also confirmed the accuracy of the velocity screens in recording velocities above 2150 feet/second. Below this velocity the shock wave established by the donor charge has a tendency to outrun the fragment and cause a false triggering of the screen. In all firings into receiver charges where fragment velocities were less than this, high speed pictures were used to establish fragment velocity.

The fragments were recovered during the calibration firings and an assessment of damage caused by launch if any, was made for each fragment. It was determined that with a 4-inch diameter and 4-inch long donor charge, the 3/8 x 3/8 x 5/16 inch thick fragment is undamaged at velocities below 5200 feet/second. The 5/8 x 5/8 x 1/2 inch thick fragment is undamaged at velocities below 3200 feet/second and the 1-1/8 x 1-1/8 x 1/2 thick fragment is undamaged at velocities below 2700 feet/second.



- Appropriate Delay Times Set on Event Sequencer
- Camera Brought up to Desired Speed
- Sequencer Started
    - Charge Set Off
    - Photo Lights On
    - Camera Shutter Opened

FIGURE 6 TYPICAL INSTRUMENT SET UP FOR HIGH SPEED PICTURES

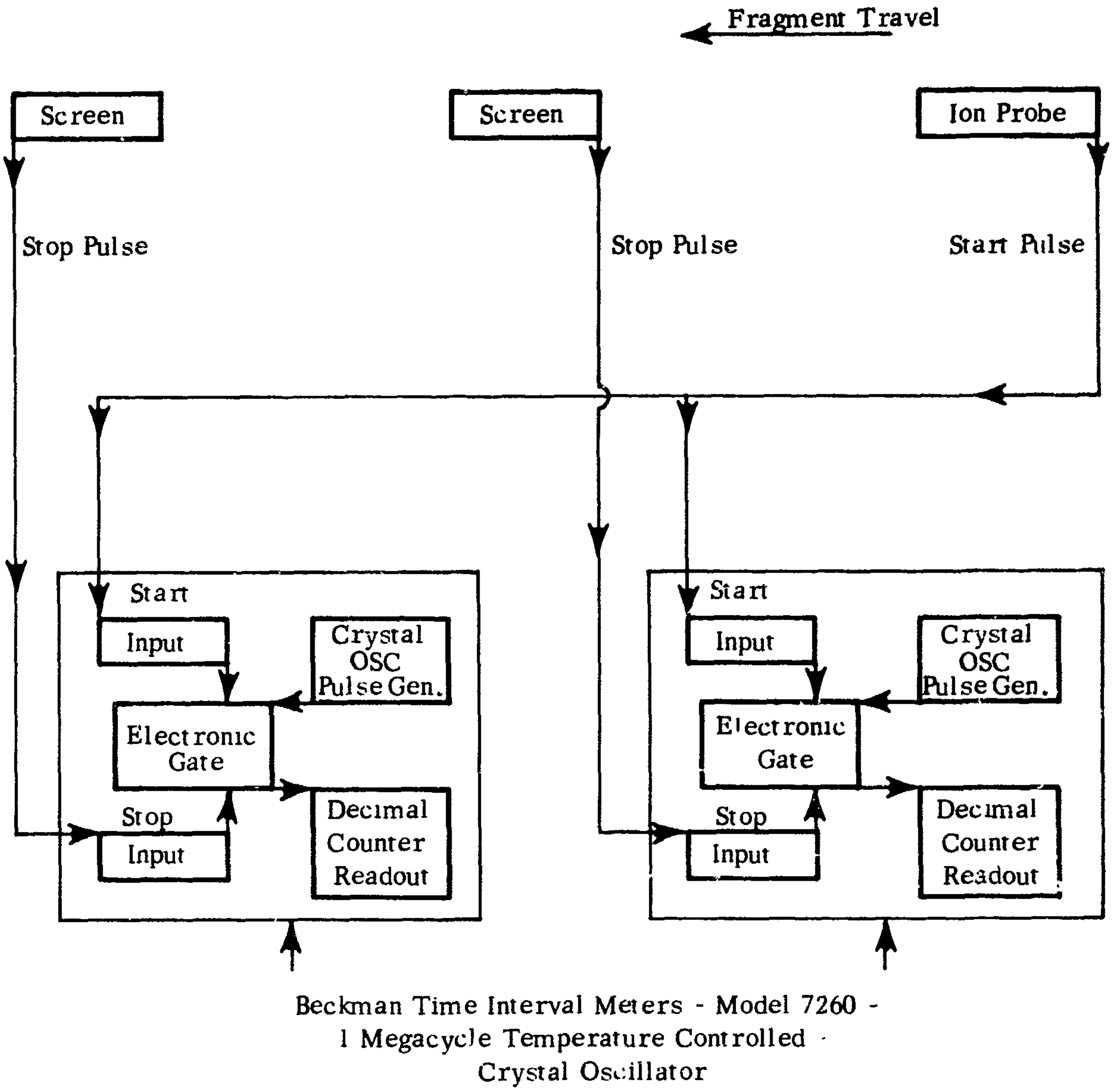


FIGURE 7 TYPICAL INSTRUMENT SETUP FOR FRAGMENT TIME OF FLIGHT

IV. RESULTS

The data from fragment impact tests where there were sufficient photographic verification and reproducibility of velocity screen measurements to insure that the recorded velocities are valid are presented in Tables I through IV. The data includes the results of tests with cased and bare receiver charges of both Pentolite and Cyclotol. The measured fragment velocities are tabulated for each test along with the boundary velocity estimated for the given fragment weight and cover plate thickness derived from the relationship established by Picatinny Arsenal.

The earlier firings with cased charges were insufficient for the establishment of boundary velocity curves but can be compared with predicted results to show trends. The later work resulted in a boundary velocity fragment weight relationship for uncased Pentolite and Cyclotol charges.

A. Tests with Cased Receiving Charges

Pentolite - The results of the applicable tests with cased Pentolite receiving charges are presented in Table I. Detonations occurred in all tests with the lighter fragment and in only one test (0.43 oz fragment and 7/16 in cover plate) was the measured value lower than would have been predicted necessary for detonation. Since the actual velocity was lower than the predicted boundary value by less than 10 percent, this one data point has little significance.

The three tests made with the heavier 2.65 oz fragment at the 1/16 in. cover plate indicate that the boundary velocity is greater than the measured value of 1640 ft/sec since no detonations occurred. This velocity is much greater than the value predicted to be necessary for detonation.

TABLE I

RESULTS OF TESTS WITH PENTOLITE

(Cased Charges)

Fragment Dimensions in.	Fragment Weight oz.	Cover Plate Thickness in.	Fragment Velocity ft/sec	No of Firings	Est. Velocity Req'd for Detonation ft/sec	Remarks
1/2x1/2x3/8 (1)	0.44	3/16	4840 (2)	1	3300	High order detonation
1/2x1/2x3/8	0.43	3/16	4840	1	3300	High order detonation
1/2x1/2x3/8	0.44	5/16	4740	1	4150	High order detonation
1/2x1/2x3/8	0.43	7/16	5660	1	6250	High order detonation
7/8x7/8x3/4	2.65	1/16	1640	3	1200	No detonation

(1) Last dimension given is the thickness of the fragment normal to the surface of the donor charge.

(2) No velocity recorded. Velocity was assumed to be the same as that of the next test listed in the table.

TABLE II

RESULTS OF TESTS WITH CYCLOTOL
(Cased Charges)

Fragment Dimensions	Fragment Weight	Cover Thickness	Fragment Velocity	No. of Firings	Estimated Velocity Required	Remarks
in.	oz.	in.	ft/sec		ft/sec	
3/8x3/8x5/16 (1)	0.2	1/16	3400	5	4400	No detonation
3/8x3/8x3/8	0.237	1/16	8400 (2)	1	4000	Burning; no detonation
3/8x3/8x3/8	0.237	1/16	8820 (2)	1	4000	High order detonation
3/8x3/8x3/8	0.237	5/16	8730 (2)	1	7400	High order detonation
1/2x1/2x3/8	0.41	1/16	4680	1	3000	No detonation
1/2x1/2x3/8	0.42	5/16	4650	1	5250	No detonation
1/2x1/2x1/2	0.5	1/16	1950	11	2750	No detonation
7/8x7/8x5/8	2.15	5/16	5250 (2)	1	2280	High order detonation
7/8x7/8x5/8	2.15	7/16	4040 (2)	1	2700	No detonation
7/8x7/8x3/4	2.65	1/16	1640	7	1600	No detonation

(1) Last dimension given is the thickness of the fragment normal to the surface of the donor charge.

(2) These firings were made with receiving charges 8 inches in diameter and 7 inches long cast at Arthur D. Little, Inc.

TABLE III

RESULTS OF TESTS WITH PENTOLITE
(UNCASED CHARGES)

Legend

Fragment Description

Type	Dimensions	Mat'l	Wt
A	3/8 x 3/8 x 5/16	Steel	0.2 oz
B	5/8 x 5/8 x 1/2	Steel	0.9 oz
C	1-1/8 x 1-1/8 x 1/2	Steel	2.85 oz

Receiver Charge Description

50/50 Pentolite
6" dia x 6" long bare

Donor Charge Description

60/40 Cyclotol
4" dia x 4" long

Buffer Material--Lucite

Firing Number	Fragment Type	Fragment Velocity Ft/Sec	Predicted Boundary Velocity (Pic Data) Ft/Sec	Remarks
16	A	3030	2850	No detonation
18	A	4110		High order detonation
19	A	3280		High order detonation
20	A	3100		High order detonation
21	A	2815		No detonation
44	A	2870		No detonation
52	A	2985		No detonation
48	A	2925		High order detonation

TABLE III (CONTD)

Firing Number	Fragment Type	Ft/Sec	Predicted Boundary Velocity (Pic Data) Ft/Sec	Remarks
29	B	1735	1730	No detonation
30	B	1785		No detonation
31	B	2750		High order detonation
32	B	2390		High order detonation
33	B	2220		High order detonation
34	B	1785		No detonation
36	B	1875		No detonation
37	B	1970		No detonation
26	C	1250	1170	High order detonation
27	C	892		No detonation
28	C	1042		No detonation
38	C	1135		No detonation
39	C	1140		No detonation--charge burned
40	C	1140		No detonation--charge burned
50	C	1100		No detonation
55	C	1040		No detonation
35	B	1875*	1730	No detonation--donor

* This velocity is estimated--conditions for firing are exactly the same as run #36

TABLE IV

RESULTS OF TESTS WITH CYCLOTOL (UNCASED CHARGES)

Legend

Fragment Description

Type	Dimensions	Mat'l	Wt
A	3/8 x 3/8 x 5/6	Steel	0.2 oz
B	5/8 x 5/8 x 1/2	Steel	0.9 oz
C	1-1/8 x 1-1/8 x 1/2	Steel	2.85 oz

Receiver Charge Description

60/40 Cyclotol
6" dia x 6" long bare

Donor Charge Description

60/40 Cyclotol
4" dia x 4" long

Buffer Material--Lucite

Fragment Velocity

Firing Number	Fragment Type	Ft/Sec	Predicted Boundary Velocity (Pic Data) Ft/Sec	Remarks
1	A	4070	3480	High order detonation
2	A	3350		No detonation--charge broken up by impact
5	A	3840		High order detonation
8	A	3585		High order detonation
9	A	3510		High order detonation
10	A	3480		No detonation
12	A	3430		No detonation

TABLE IV (CONTD)

Firing Number	Fragment Type	Ft/Sec	Predicted Boundary Velocity (Pic Data) Ft/Sec	Remarks
3	B	2540	2110	High order detonation
4	B	2150		No detonation--charge completely broken up--recorded velocity may be shockwave
6	B	2000		No detonation--charge burned 35 min.
7	B	2150		No detonation
11	B	2425		High order detonation
13	B	2340		No detonation
15	B	2330		No detonation
41	C	1250	1430	No detonation--fire in impact area--charge consumed
42	C	1390		No detonation--fire in area fragment recovered
43	C	1560		No detonation--charge burned fragment recovered
45	C	1505		No detonation--charge burned very quickly
46	C	1390		No detonation
47	C	1430		No detonation
49	C	1500		No detonation--charge burned
51	C	1630		No detonation--charge burned very quickly

TABLE IV (CONTD)

Firing Number	Fragment Type	Ft/Sec	Predicted Boundary Velocity (Pic Data) Ft/Sec	Remarks
53	C	1785		No detonation--charge burned
54	C	2080		No detonation--charge burned
56	C	2640		Yes--high order detonation 0.88 to 1.0 microseconds to detonation
57	C	2450		High order detonation
58	C	2180		No detonation
59	C	2280		High order detonation
60	C	2080		No detonation
14	B	2330*	2110	No detonation

* This velocity estimated--conditions for firing are exactly the same as run #15

Cyclotol - The results of the applicable tests with cased Cyclotol receiving charges are presented in Table II. In the tests using the lighter (0.2 to 0.5 oz) fragments all but two firings produced results that are consistent with the Picatinny Arsenal relationship. That is, either detonation occurred when the velocities were higher than predicted to be necessary or no detonation occurred when the velocities were lower than the estimated boundary values. One test with the 0.237 oz fragment and one with the 0.41 oz fragment did not result in full detonation when the impact velocities were higher than predicted values. These two tests were insufficient in number to allow conclusions to be drawn as to their significance.

In the tests with the heavier fragments, the velocities were all higher than the predicted boundary values. Detonation occurred, however, in only one instance (5/16 cover plate) and here the velocity was more than twice that estimated to be necessary. The results of this and the other eight tests indicate that the actual boundary velocities for the heavier fragments may be higher than predicted by the Picatinny Arsenal relationship.

B. Tests with Uncased Receiving Charges

A total of 55 valid tests were made with bare charges of Pentolite and Cyclotol using fragment weights of 0.2, 0.9 and 2.85 ounces. The results of these tests are presented in Tables III and IV.

With the exception of one test, the velocities (for a given fragment weight) where detonation occurred were always higher than those where detonation was not experienced. This would lead one to believe that in most cases, the actual boundary velocity for a given fragment weight exceeds the highest velocity where detonation did not occur. The highest velocities that did not produce high order detonation and the lowest where detonation

did occur are presented in Table V. An estimated boundary velocity curve for each explosive is drawn in Figures 8 and 9.

From both Table V and Figures 8 and 9, it may be seen that there is a significant departure in measured boundary velocities from those predicted by the Picatinny Arsenal relationship for the heavier fragments. With the 0.2 ounce fragments no significant difference can be found between the experimentally determined and predicted values. With Cyclotol charges the experimentally determined boundary velocities are approximately 12 and 55 percent greater for the 0.9 and 2.85 ounces fragments respectively. The experimental values for Pentolite result in a 25 percent higher boundary velocity than predicted for the 0.9 ounce fragment and no significant difference in experimental and predicted values for the 2.85 ounce fragment.

TABLE V

COMPARISON OF VELOCITY DATA

(Uncased Explosive)

Explosive Type	Fragment Weight	Lowest Velocity with Detonation	Highest Velocity without Detonation	Boundary Velocity from Picatinny Arsenal Data
	oz	ft/sec	ft/sec	ft/sec
Pentolite	0.2	2925	2985	2850
	0.9	2220	1970	1730
	2.85	1250	1140	1170
Cyclotol	0.2	3510	3480	3480
	0.9	2425	2340	2110
	2.85	2280	2180	1430

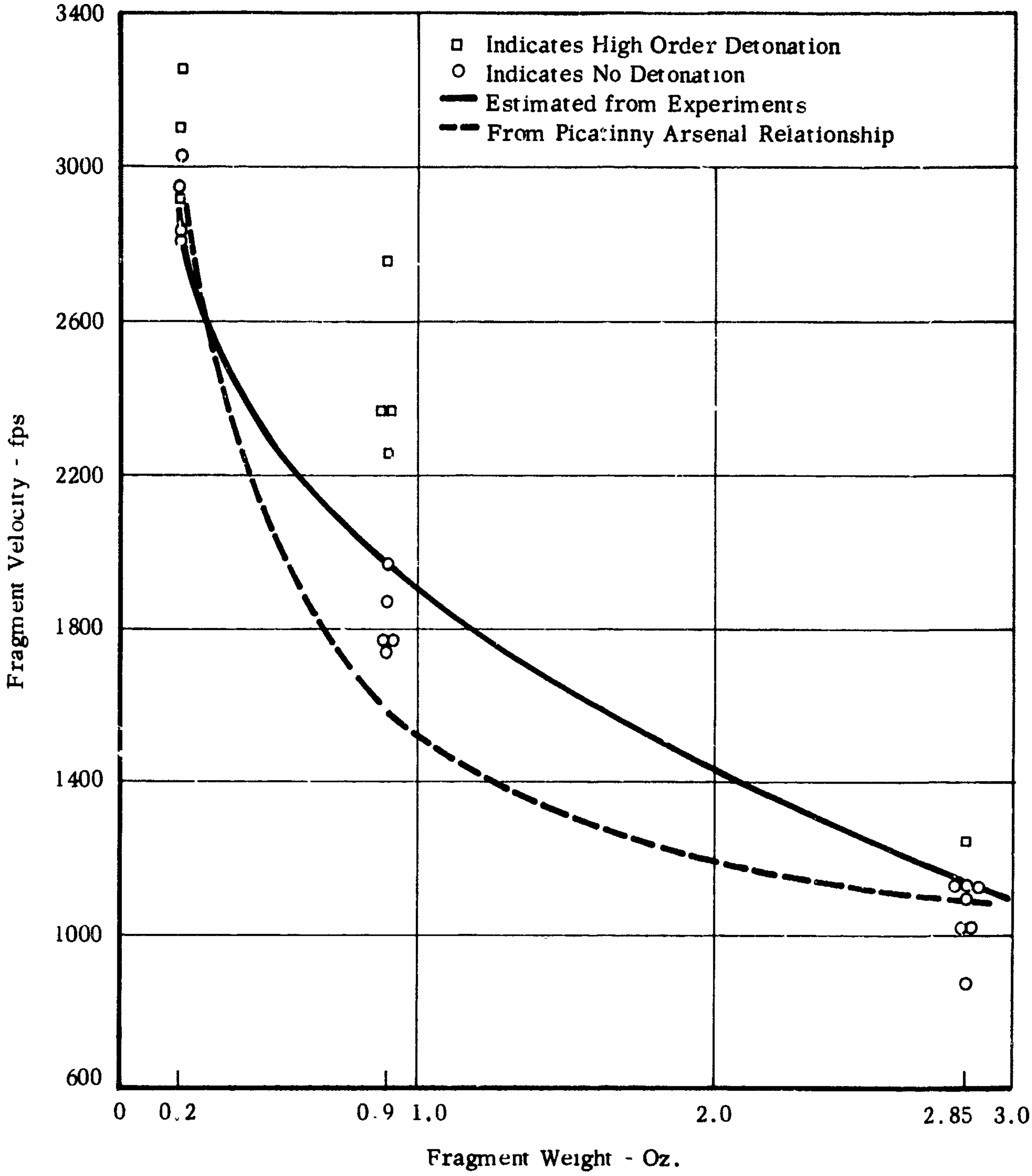


FIGURE 8 BOUNDARY VELOCITY CURVE OF PENTOLITE, SHOWING FRAGMENT IMPACT VELOCITY VERSUS FRAGMENT WEIGHT

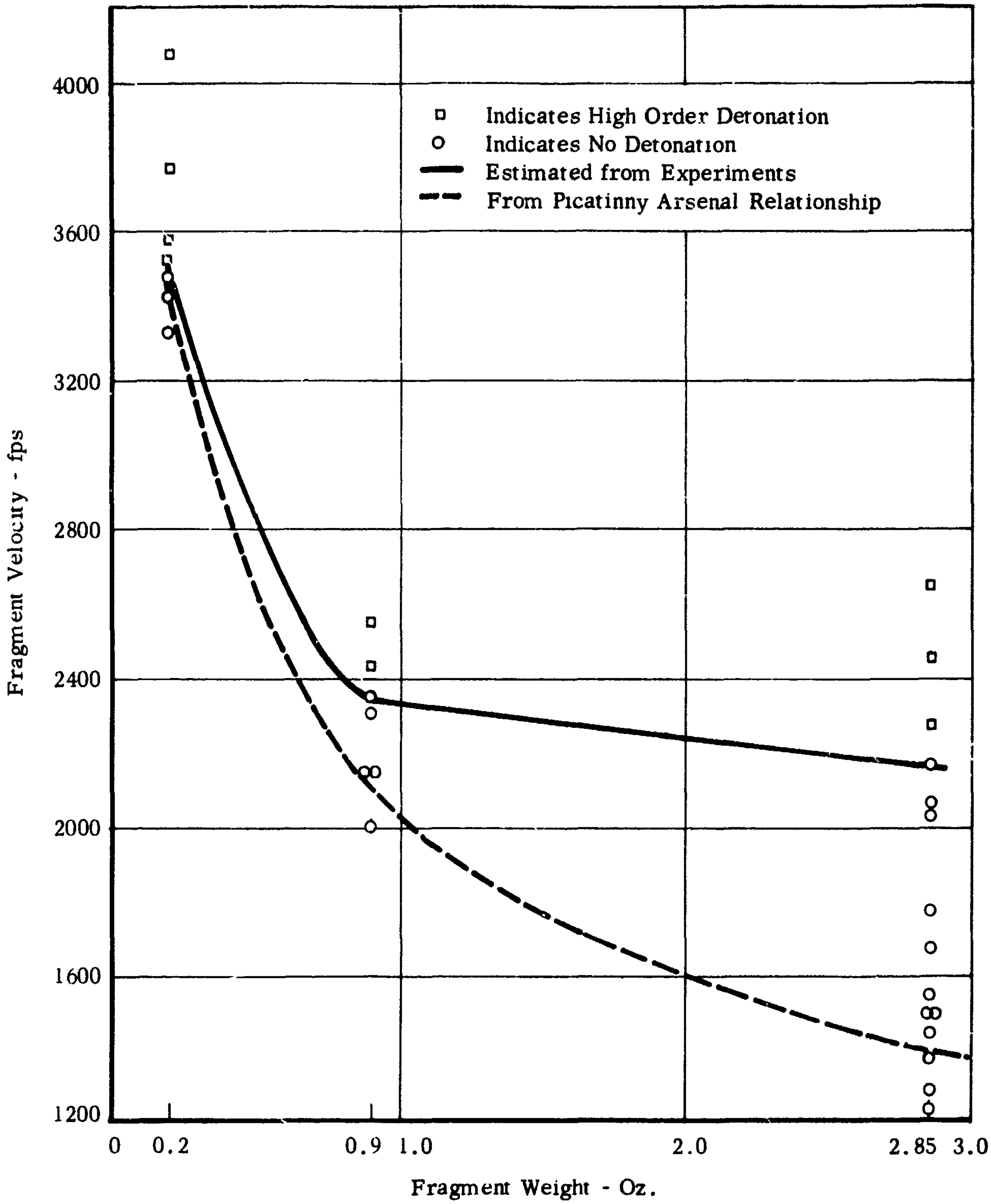


FIGURE 9 BOUNDARY VELOCITY CURVE OF CYCLOTOL. SHOWING FRAGMENT IMPACT VELOCITY VERSUS FRAGMENT WEIGHT

V. CONCLUSIONS

1. The results of tests with small (0.2 oz) and intermediate (0.9 oz) fragments fired into cased and uncased Pentolite and Cyclotol tend to confirm the boundary velocities predicted by the Picatinny Arsenal relationship.

2. Good agreement between the experimental results and that predicted by the Picatinny Arsenal relationship was achieved with all fragment weights fired into uncased Pentolite.

3. The boundary velocity for heavy fragments (2.85 oz) fired into Cyclotol were higher than predicted. This would indicate that the mass-velocity relationship may need to be adjusted for a more accurate prediction of sensitivity to impact by heavy fragments. The current predicted values for the boundary velocity tend to be conservative and hence are satisfactory for design purposes where safety is the prime consideration.

4. The tendency for the experimental boundary velocity of Cyclotol to increase over the predicted values as the fragment weight increases would indicate that more tests should be made to insure that the trends established in this work for both explosives are statistically valid.

APPENDIX A

DEVELOPMENT OF THE EXPERIMENTAL TECHNIQUE

A. Background

Explosive techniques for the launching of metal fragments at high velocities have been the subject of considerable experimental and analytical effort in the development and studies of explosive warheads. This work has shown that the acceleration of fragments in the range of weights and sizes of interest in this program can be accomplished reproducibly for a large percentage of the velocities required.

Prior to this program, it had been established at Arthur D. Little, Inc.* that rectangular steel fragments of 3/4" x 3/4" x 1/4" and 1/2" x 1/2" x 1/4" could be accelerated reproducibly up to velocities approaching 8000 ft/sec without breakup or measurable erosion. The experimental technique used in this program is based on the direct application of the methods that were used for this work. Some modification was required, however, to allow the velocity of the fragment to be varied and to enable fragments of greater thickness to be accelerated. In addition, the limitations imposed by the small (target) diameter of the receiving charge (as supplied by the Arsenal) required that the donor and receiver be relatively close to one another in order to achieve a high percentage of impacts. This resulted in the requirement that the velocity screens be placed much closer to the donor than had been the practice in previous work. The derivation of a satisfactory surround (fragment protection) that would not interfere with the action of the velocity screens under these conditions was much more difficult than originally expected.

*Arthur D. Little, Inc., Development of 300 lb.-T33 Fragmentation Warhead Contract DA-19-020-501-ORD-(P)-41 c

B. Mechanics and Limitations of Explosive Launch

The explosive acceleration of fragments depends upon the forces imposed by the shock wave generated by the detonation. In the technique used in this program, the explosive reaction is initiated at the end of the charge opposite to that of the fragment. Ideally, the detonation wave front would be plane as it reaches the forward face of the explosive. Actually, some curvature was present because of localized initiation (for a short charge) and loss of energy to the atmosphere at the sides of the charge.

The detonation wave is characterized by a constant velocity (25,000 ft/sec) and a peak pressure (300,000 atm) for Composition B. The pressure-time integral (or thickness) of the wave increases as more energy is added. For a cylindrical charge of finite diameter, the strength of the detonation wave does not increase after a given distance of travel. The limiting strength is reached when the losses from the sides of the wave become equal to the energy being added by reaction of additional mass. This condition was generally achieved in our tests when the length of the charge was equal to its diameter.

When the detonation wave reaches the forward face of the explosive, it causes a shock wave to propagate through the separator that precedes the fragment. The shock wave consists of a very high peak pressure attained in a very short period of the time followed by a pressure decay. A rarefaction wave (negative pressure) follows the shock. The energy transferred to the shock wave from the explosive is a function of the physical and thermodynamic characteristics of the spacer material at its

shocked state relative to those of the gases in the detonation wave. The optimum energy transfer occurs when there is a proper impedance match.

Because of energy losses, the shock wave decreases in strength as it passes through the separator. This results in a decrease in peak pressure, pressure-time integral and velocity of the wave.

When the shock wave reaches the separator-fragment interface a new shock wave is set up in the fragment. The energy in this new shock wave is again a function of the impedance match between the two materials. When the shock wave reaches the forward face of the fragment some of the energy goes into producing an air shock and the remainder is reflected at the interface. Reflections of decreasing strength through the spacer-fragment system (depending upon the duration of the shock wave in the explosive) continue to occur. During this interval the fragment is accelerated by each shock reflection.

Finally, the rarefaction wave from the explosive is transmitted to the fragment. At some point within the fragment it may meet and reinforce the rarefaction wave associated with one of the shock reflections from the forward surface. This will produce a large tensile force within the fragment. Generally, if the decay rate of the explosive pressure pulse is short so that this occurs during the first reflection the tensile forces will be great enough to make fracture l ely.

The probability of fracture of the fragment increases as its thickness increases and as the peak pressure of the imposed shock is increased relative to the shock duration. Thus, a larger explosive charge and thicker spacers must be used with thick fragments to achieve higher velocities without

fracture. The thickness of fragment achievable (without failure) for a given velocity, increases in direct proportion to the dimensions of the explosive. That is, doubling all dimensions of the explosive and spacer will allow the maximum thickness of fragment that can be accelerated to a given velocity without break up to be doubled.

Deformation of the fragment may also occur as the result of unequal pressure forces at its edges. The large pressures associated with the shock wave will cause deformation unless the fragment is surrounded by a material that will also transmit a shock wave of similar characteristics. When the steel fragment is surrounded by steel, the pressures are equal and little or no deformation occurs. When surrounded by a less dense material (plaster), deformation will tend to occur under the more severe conditions (high velocities).

When a fragment of a given thickness is surrounded by like material, the maximum velocity that can be achieved is primarily dependent on the explosive charge dimensions, and the spacer thickness and composition. The lateral dimensions of the fragment are limited by the diameter (with an appropriate length) of the explosive necessary to induce the proper shock wave in the surround. Thus, the mass of fragment could be increased significantly without a reduction in velocity if the lateral dimensions were increased beyond the limiting values established by the length to width ratios of 0.8 to 1.5.

The maximum velocity that could be achieved with the thinnest fragment allowed in this work was limited by the largest practical size of the donor that may be used. Higher velocities might be achieved, however, through

refinements such as increasing the strength of the steel fragments and altering the spacer material to provide better impedance matching.

C. Establishment of the Experimental Method

1. General

In the course of this work three different explosive launch configurations were used. The initial work was carried out with a 3.5 inch diameter explosive donor charge using plaster-of-paris as both the surround and separator. Later, steel was substituted for the plaster surround and lucite for the separator. An eight inch diameter charge was used in the most recent tests. Steel surround and lucite separators were also used with this larger charge.

Prior to the firing of fragments at receiving charges with each of the above configurations, tests were made to establish the maximum velocities that could be achieved without deformation or break up and to determine the variation in velocity with spacer thickness and, in some instances, with length of the donor. Fragments were recovered and examined to assess deformation and change in weight.

In some cases where thickness of fragment was of principal interest preliminary data were obtained using fragments with cross sectional areas that resulted in length to width ratios larger than specified. Data from the tests to establish the technique also provided information as to the prediction of velocity for a given spacer thickness and charge length as well as the accuracy of the velocity measuring system since velocities were measured by both photography and screens.

2. <u>Tests with Plaster Surround</u> (3.5 in diam. donor)

The initial approach used in this program was based on the premise that the use of a frangible surround and spacer would avoid the problem of secondary fragments interfering with velocity measurements or impacting at the receiving charge. On detonation of the donor the frangible material would pulverize and, because of the resulting high drag to weight ratio, the dust cloud would rapidly lose velocity and would be well behind the fragment after a relatively short distance of travel.

The use of a frangible surround represented a departure from the technique used in our previous work. It was reasoned that the metal surround used in the past would produce secondary fragments that would both impact with the receiving charge and interfere with the velocity measurements.

A plaster-of-paris was selected for the frangible surround. Initial tests, where the velocity screens were examined, indicated that the surround performed satisfactorily. As testing progressed it was found that the recorded velocities were not always reproducible. However, incremental increases in velocity with length of donor, reduced fragment weight, or reduced thickness of surround appeared to be consistent and, in general, followed estimates based on Sterne's flat plate formula.

On firing at both Cyclotol and Pentolite receiving charges, however, detonation did not occur at velocities well in excess of those predicted by the Picatinny Arsenal relationships. Changes in the velocity screens and blank firings (tests with the surround but no fragment) did not reveal deficiencies in the technique.

Later tests using high speed photographic techniques, however, revealed that the velocities derived by contact screens were in error and were too high. Evidently, pieces of the surround that had been accelerated to higher velocities than the fragments had falsely triggered the screens. The photographic measurements were used to establish the velocities that had actually been achieved with the plastic surround allowing some of this data to be used in the determination of the boundary velocities for Cyclotol and Pentolite.

The velocities recorded by high speed photographs of fragments fired with the plaster surround are given in Table AI. From this data and previous tests to establish the maximum velocities achievable with this configuration it was estimated that a velocity of about 3500 ft/sec could be attained with the 0.2 oz fragment, and 1650 ft/sec could be attained with the 2.6 oz fragment. These velocities were well below those required for the investigation of Cyclotol and TNT. In order to achieve higher velocities and to obtain correct readings from velocity screens the surround and spacer materials were changed.

3. <u>Tests with Metal Surround</u> (3.5 in diam. donor)

The experimental technique was then altered so that a metal surround could be used in a similar manner to that developed in previous programs. It was found that by allowing the sections of steel surround to extend beyond the outer boundaries of the charge, the secondary fragments departed significantly from the trajectory of the primary fragment. In 30 tests where the impact of the metal surround was measured, no secondary fragment

TABLE A1

PHOTOGRAPHIC MEASUREMENT OF FRAGMENT VELOCITY

PLASTER SURROUND

Firing Number	Fragment Dimensions inches	Fragment Weight ounces	Explosive Change Length inches	Thickness Of Plaster inches	Velocity ft/sec
T-2	1/2x1/2x1/2	0.5	3	1-1/4	1940
T-4	1/2x1/2x1/2	0.5	3	1-1/4	1950
T-32	7/8x7/8x3/4	2.6	4	1-1/4	1640
T-33	3/8x3/8x5/16	0.2	4	1-1/4	3440
T-38	3/8x3/8x5/16	0.2	4	1-1/4	3380

came closer to the point of impact of the primary fragment than approximately 7 inches at a distance of 6 feet from the donor.

An initial series of tests were made with the metal surround to establish the minimum thickness of lucite that could be placed between fragments of different thicknesses and the explosive without fragment fracture occurring. An explosive charge of 4 inches in length was used and all fragments had a cross sectional area of one square inch. No velocities were recorded. Fragments were recovered and examined after each firing.

A second series of tests were then made to establish the velocities achieved when different thicknesses of lucite were used. All firings were made at velocity levels below that which would cause spalling. Velocities were measured both with screens and by high speed photographs. The results of this series of tests are presented in Table AII. The velocities measured by the camera are, in general, higher than those recorded by the screens, since the portion of the fragment trajectory recorded by the camera was closer to the donor explosive than that covered by the screens. The standard deviation computed on the basis of the difference between the two velocity measurements is estimated to be 85 ft/second. This corresponds to a variation of approximately 2% at a velocity of 4000 ft/sec. A tolerance level of 2% has been specified for thiswork.

The data from the two series of firings with metal surround were plotted in Figure 1A in order to provide a working graph for the selection of lucite thickness to attain a desired velocity for a given fragment thickness. The coverage of masses and velocities of fragments that has

TABLE A2

PHOTOGRAPHIC MEASUREMENT OF FRAGMENT VELOCITY

METAL SURROUND

(All explosive charges 4 inches long, 3.5 inches dia.)

Firing Number	Fragment Dimension	Fragment Weight	Lucite Thickness	Velocity by Screens	Velocity by Camera	Velocity Difference
	inches	ounces	inches	ft/sec	ft/sec	ft/sec
T-19	1x1x1/4	1.1	0.060	5910	5910	0
T-20	1x1x1/4	1.1	0.060	----	5910	-
T-21	1x1x1/4	1.1	0.060	----	5800	-
T-22	1x1x3/8	1.74	0.030	4640	4775	+135
T-23	1x1x3/8	1.74	0.030	4700	4910	+210
T-24	1x1x3/8	1.74	0.030	4660	4630	- 30
T-26	1x1x5/8	2.9	0.030	1745	1710	- 35
T-27	1x1x1/4	1.1	0.125	5640	5640	+ 10
T-28	1x1x1/4	1.1	0.750	4300	4260	- 40
T-29	1x1x1/4	1.1	1.187	3640	3820	+185
T-30	1x1x3/8	1.74	0.650	3680	3780	+100
T-31	1x1x3/8	1.74	1.00	----	3110	-
T-34	1x1x1/3	1.1	2.00	2440	2470	+ 30
T-35	1x1x3/8	1.74	2.00	1875	----	-
T-36	1x1x5/8	2.9	2.00	1870 (air shock velocity)	1310	-
T-37	1x1x3/8	1.74	1.50	2410	2420	+ 10

$\sigma = 85$

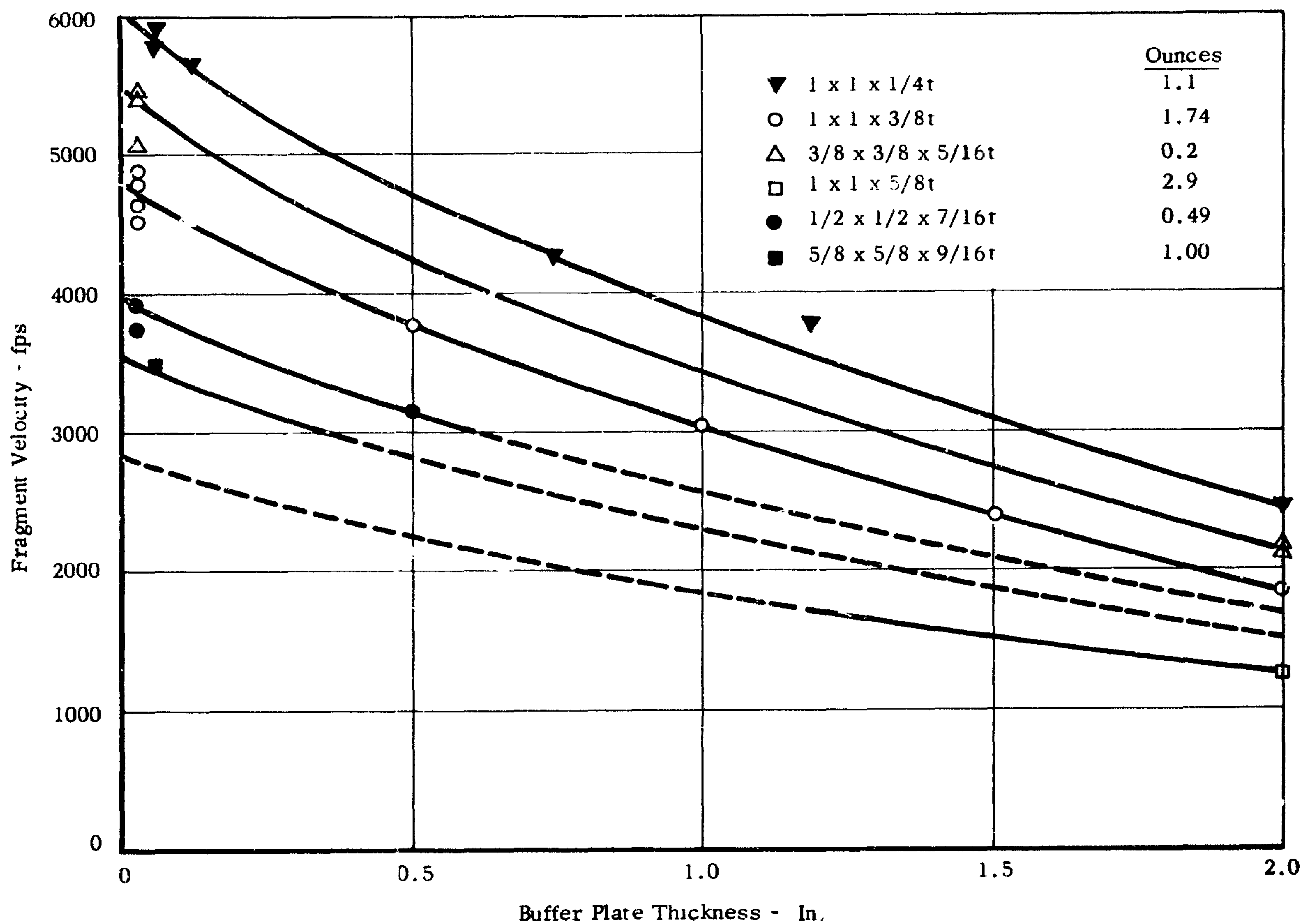


FIGURE 1A FRAGMENT VELOCITY VERSUS THICKNESS OF LUCITE--All Propelling Charges 3.5" Diameter x 4" Long (Dashed Portion of Curves Have Not Been Confirmed by Actual Firings). All Fragments Undamaged.

been proven to be attainable from the above tests is shown in Figure 2A. It is estimated that the maximum velocities achievable (without spalling) for this configuration are of the order of 5500 ft/sec for a 0.2 oz fragment and 1700 ft/sec for a 2.6 oz fragment.

4. Tests with Metal Surround (8 in diam. donor)

The maximum velocities achieved with the 3.5 inch diameter donor charge and metal surround were not sufficient to provide the coverage needed in the basic program. A significant increase in donor charge dimension was required in order to produce an accelerating shock wave of the required strength. An eight inch diameter charge was selected for tests with a steel surround and lucite separator.

Firings were made to determine the maximum velocity that could be achieved without breakup and this was found to be about 8800 ft/sec for a 0.25 oz fragment and 5000 ft/sec for a 2.15 oz fragment. These velocities were sufficient for the completion of the tests with Cyclotol and Pentolite.

D. Additional Data

In a few tests with the eight-inch diameter donor and Cyclotol receiving charges, some information relative to the effect of the experimental technique on the initiation of detonation by fragment impact was obtained. The time to detonation was measured in 3 tests with the .24 oz fragment and in one test with the heavy (2.15 oz) fragment by the use of a pressure switch placed adjacent to the receiving charge to detect the shock wave from the receiver detonation. In all cases, the time between fragment impact and switch closure was less than 200 micro seconds. This short time

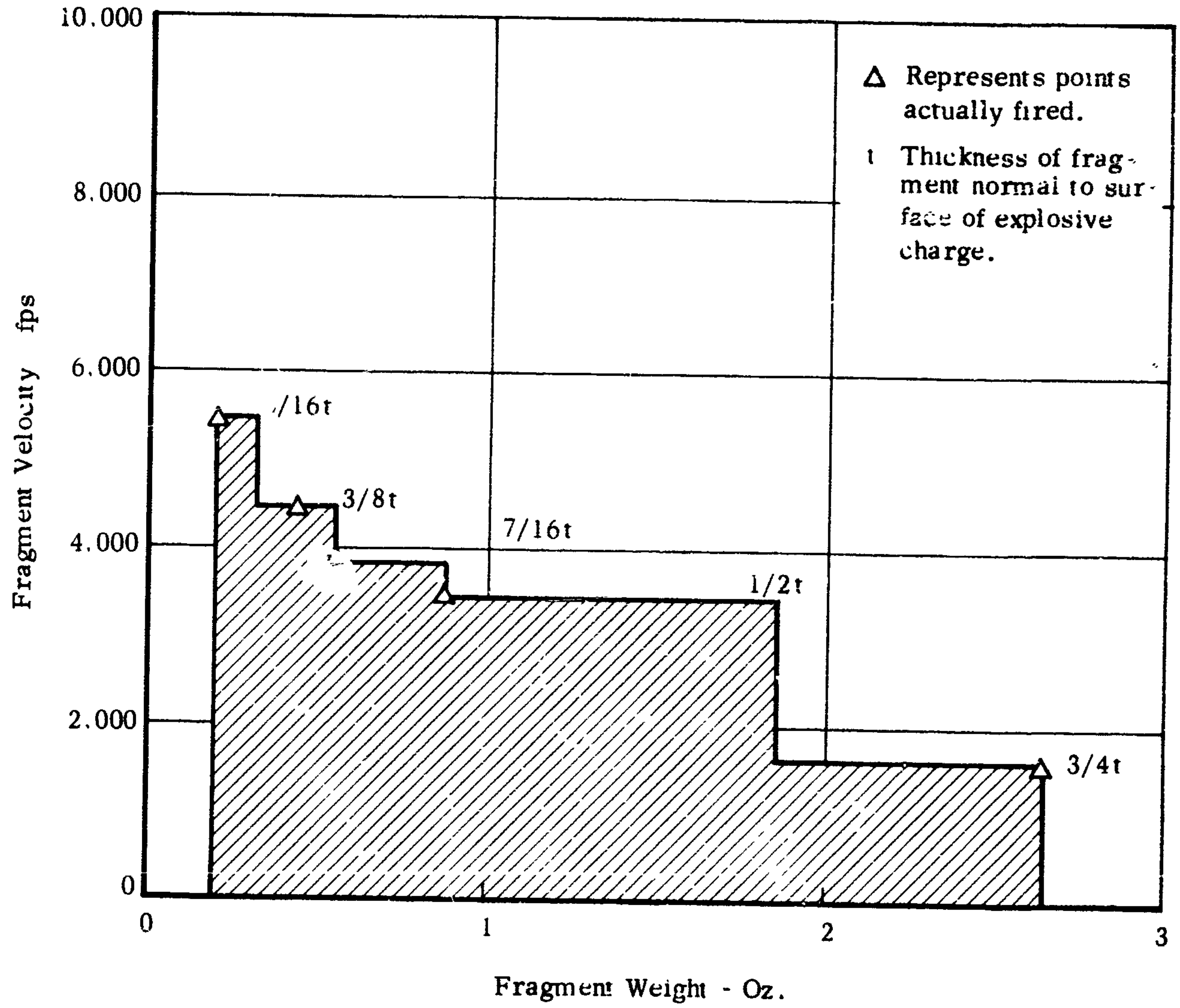


FIGURE 2A MASSES AND VELOCITIES OF UNDAMAGED FRAGMENTS OBTAINABLE WITH A 4-INCH DONOR CHARGE (Metal Surround)

interval indicates that detonation was initiated by the shock wave generated by fragment impact. It is believed that this mode of initiation differs from that noted by other experiments where much longer times between fragment impact and receiver detonation indicate a thermal process may cause detonation.

In the test with the 2.15 oz fragment and the 7/16 inch cover plate, it was noted that the fragment had apparently completely penetrated the full length of the charge and had caused deformation of the witness plate to the rear without detonating. Such complete explosive penetration could sometimes cause detonation by pinching or compression of the explosive between the fragment and the witness plate.

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Donald S. Allan & Donald G. McLean

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Final Report - December 29, 1965 Contract No DA-19-020-ORD-5617
PA Control No PA-AG-62-1 Picatinny Arsenal Dover, New Jersey

An experimental program was conducted to establish the sensitivity of explosives to the impact of regular steel fragments. Non-spinning rectangular fragments of 0.2 to 3.0 ounces were projected by explosive means at velocities both above and below that required for detonation. Velocities were measured by screens and by high speed photography.

All data were obtained using either Pentolite or Cyclotol explosives. The results of the tests were compared with a relationship between fragment mass and boundary velocity (below which detonation will not occur) established by Picatinny Arsenal and based on data from small fragment tests. The tests with uncased charges tended to confirm the predicted relationship for all fragment weights fired at Pentolite and for the small and intermediate fragments fired at Cyclotol. A modification in the predicted mass-velocity relationship may be required to more accurately define the boundary velocity for heavy fragments (3.0 oz) impacting in Cyclotol.

These tests demonstrated that with uncased charges the Picatinny Arsenal relationship will tend to be conservative when used to predict boundary velocities for safety purposes.

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